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Review Article

Smart City: Recent Advances in Intelligent Street Lighting Systems Based on IoT

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Based on the importance of energy saving in terms of reducing the carbon impact and global warming problems, smart street lighting systems have been proposed in the past few years with different specifications. These systems include sensors for controlling the light intensity and connectivity for recording weather conditions and diagnosing lamp failure remotely. This paper discusses many published research studies regarding smart street lighting systems, providing a comparison between these systems which emphasizes the limitations of each one of them. Current and future trends are highlighted.

1. Introduction

Street lighting is a core infrastructure piece in urban and semiurban cities. It provides a number of advantages such as improving safety for drivers and pedestrians. Nowadays, street lighting accounts for about 13–14% of the world's electricity annual production [1–4], and the market is continuously growing. It is expected that by 2027, there will be about 363 million street lights around the world [5]. Consequently, enormous energy is consumed by the street lights, which makes it imperative to work on solutions to reduce street light consumption.

Developing smart street lighting with a control system is another topic of major interest to many researchers around the world. The lighting control network is an excellent upgrade to street lighting. Deploying a control system can offer great solutions that contribute to safety and sustainability.

This paper reviews the current trends in smart street lighting with emphasis on the selection of the type of lamp and the method of controlling the light intensity, as well as the approach to connect the sensors together to remotely control the lights, record the weather conditions, and diagnose lamp failure remotely. A comparison between the different methods is provided in Section 6.

Compared to other review papers on smart street lighting [6–8], our paper compares the different systems of smart street lighting including control mechanism and connectivity and discusses the current and future trends. The other review papers excluding [6] mainly focus on one type of connectivity and one type of control system. This is shown in Table 1.

This paper is divided as follows. Section 2 discusses the selection of light lamps. Section 3 discusses background work on smart street lighting explaining the different control techniques. Section 4 introduces the concept of networked

Table 1: Comparison between the different review papers on smart street lighting.

Review paper #	Lighting system	Control system	Connectivity	Current trends	Future trends
[4]	Lamps & LEDs	Different systems	Different techniques	✓	x
[5]	LED only	PIR sensor only	ZigBee only	x	x
[6]	LED only	Time-scheduled dimming only	IoT only	x	x
This paper	Lamps & LEDs	Different systems	Different techniques	✓	✓

street lighting systems as well as its state-of-the-art. Section 5 discusses different light connectivity techniques. Section 6 summarizes the properties of the different lighting systems. Section 7 highlights the current and future trends in smart lighting systems. Finally, the conclusions are provided in Section 8.

2. Selection of Light Lamp

The selection of the right bulb is the first key to having an energy-efficient lighting system. Moreover, given the fact that pedestrian discomfort and glare may lead to fatal accidents in urban cities, according to [9, 10], the light-type selection is a very critical component in all streets. Currently, most of the cities are still using the traditional street light bulbs that are mainly either High Pressure Sodium (HPS) or Metal Halide (MH) bulbs. These types of bulbs are considered inefficient since they consume a lot of energy. Besides, they have a short lifetime compared to Light Emitting Diodes (LEDs) and require extensive maintenance periodically, which consequently increase the cost. For instance, an HPS lamp has a lifetime between 12,000-24,000 hours, produces 45-160 lumens per Watt, and requires up to 15 minutes ignition time [11]. It also has a low Color Rendering Index (CRI) for yellow light, contains mercury and lead, and requires up to 400 W of power [11, 12]. In contrast, the LED is considered as one of the best options for light selection due to its advantages [11, 12]. Unlike traditional lamps, LED lamps have the following features:

(i) Offer longer lifetimes between 50,000 and 100,000 operating hours

(ii) Produce 37-120 lumens/watt from the light source and ballast

(iii) Lower power consumption and emit less heat

(iv) Lower maintenance frequency requirement compared with conventional street light technologies

(v) Higher durability since they do not contain any glass, instead they are fixed on a circuit board

Some of the important factors to be considered in determining a LED light's suitability for street lighting include correlated color temperature (CCT), mesopic vision luminance, dark adaption, color perception, fog penetration, and sky glow pollution [13, 14]. Examining these factors, researchers [15, 16] have found that the human eye has decent dark adaption time and color discrimination abilities under LED street lights of around 3000°K CCT. At this temperature, LED light has a relatively high luminous efficacy and is suitable for roads.

In the literature, a full street lighting system using LEDs is simulated using MATLAB [13]. The simulation compares the results between LEDs and other types of traditional lamps used in the streets. Results prove that the LED has better efficiency and power consumption compared to other available bulbs in the market. A prototype of a new efficient and adaptive LED luminaire for street lighting was proposed by [17]. The design is providing a homogeneous luminance level needed for drivers and pedestrians. The LED can produce a light pattern that improves the driver's visualization with maximum eye comfort. A survey on the risks of distraction and poor visibility at night showed that LED street lighting improves safety for drivers and pedestrians [18].

Motivated by the LED advantages, outdoor light companies are currently offering new and efficient LED lights that can replace the old inefficient lights [11, 12]. In the coming years, LEDs are rapidly becoming the dominant source of lighting in many smart areas in which the global investment is expected to be around 53.6 billion dollars [5]. The potential advantages of white LED-based photometric standard lamps were investigated in [19]. Moreover, an extensive study to increase the efficiency of street lighting by optimizing the luminous flux distribution of luminaires and its influence on the light trespass was carried out in [20].

In addition to the many advantages that LED lighting has over conventional lighting, it faces several challenges. These include the high temperature-sensitive nature in both performance and reliability as well as the poor light coupling through the LED surface which decreases the external quantum efficiency.

3. Smart Street Lighting Control Mechanisms

Smart street lighting is defined as a network-based system of street lights which is equipped with sensors and actuators, thus offering a wide set of capabilities and connectivity interfaces. In this section, we explain the different control mechanism for smart street lighting. Centralized control with the aid of short-range and long-range wireless communication in its lighting system was employed [21]. Local control of light intensity through localized sensors that are available on each pole was used [22]. A ZigBee network was used here to send the collected information on each pole to a coordinator pole which had a Raspberry Pi card to transmit the information through a WiMAX modem to a remote server available on the internet. Controlling light through a wireless communication system with DALI protocol was proposed [23]. The control of light via a wireless sensor network that consisted of a node for each light pole was proposed [24]. Each node includes a vehicle detection subsystem, a wireless communication and control subsystem, and a lighting subsystem. A smart predictive monitoring and adaptive control system was implemented [25]. In this system, a smart camera is used to obtain information about traffic conditions. Artificial intelligence makes it possible, thanks to computer processing, to discriminate the movement of trees, identify animals (cats and dogs), and only turn on the lighting for humans and vehicles without facial recognition [25]. A set of sensors connected via a ZigBee network and a web-based management system to control the street lights was used [26]. The intensity of light via LDR and IR sensors was monitored [27]. The quality of air was monitored and conveyed here through an IoT system. Light control using a system of SCADA, IoT, and Raspberry Pi was carried out [28]. The proposed system was 43% more efficient than conventional systems. A light control was achieved via a power converter operating in discontinuous conduction mode with dimming capability, sensors, and digital processor [29]. Light control was achieved through an algorithm that could provide energy to each lamp pole during the night with the aid of sensors and solar trackers [30]. The communication was done here using XBee wireless module. Light system control was achieved via PIR sensor, LDR sensor, pollution sensor, and a camera [31]. A street lighting management system that consisted of one web-based cloud management platform, one set of edge devices (a single-board computer, a microcontroller, sensors, and an IP camera), and a real-time lighting control function was proposed [32]. It was also proposed to extract travel parameters from the signatures of received signal strengths that stem from the behaviors of vehicles and pedestrians moving on the road, and dimming street lights accordingly [33]. In this system, the electric energy consumed was only 10.5% of that consumed by existing methods. A high-power (60 V/1 A) single-chip driver for LED dimming was presented [34]. To keep high-stable LED lighting, the dimming techniques used current mode rather than PWM (Pulse Width Modulation) to reduce flicker. More research work has been carried out on smart street lighting [35–55].

Any lighting system design has to comply with the CEN/TR 13201 lighting standard proposed in 2004 and later modified in 2014. Compliance with the standards is a prime objective, since it provides both safety and convenience. It deals with lighting parameters, such as pole placement, height, overhang, tilt, rotation, fixture make and model, and light source power settings. [56].

4. Networked Street Lighting Systems

Given the numerous advantages of smart street lighting compared to traditional lighting, many researchers are working towards designing and developing new smart street lighting systems, including data collection. For example, the cost of the street light would be higher if it is not deploying any intelligent light control system. The light control system can help in identifying the required illumination level for different street zones at a specific time with a certain duration. Consequently, it reduces maintenance costs. Another point is that real-time information on energy usage can help in optimization and grid management. An efficient system for smart street lights was proposed by [32]. This system includes configuration, deployment, and management. It provides real-time environment data as well as enables live image streaming. Solar smart LED street light system was presented in [57]. Results show that massive energy is saved using this system. Unlike the wired light system, an intelligent street light system that is based on GSM technology was proposed in [58]. It contains two Light Dependent Resistors (LDRs) which are used for switching off/on the light and checking the lamp health status. Results show that the proposed system has lower maintenance cost and lower energy consumption. Moreover, street lighting with GPS/GPRS/4G technology was presented in [59].

Multiple cities have started to use sensor-controlled dimming of street lighting such that light intensity changes according to the street traffic conditions [60–69]. The majority of the systems proposed for automatic light dimming were centralized systems that treat each light lamp as a node and the nodes are connected through a wireless sensor network [60, 62, 65, 68]. The use of centralized controlled lighting systems has some drawbacks. The system response is slow in the sense that it may not be able to track fast-moving vehicles. It requires more energy to operate and maintain. In addition, the on-off switching or dimming of centralized large systems may cause hazardous spikes that could damage the lights and transformers on the grid [66]. Some centralized dimming systems use microcontroller units to control the data received from different light nodes [65]. Moreover, the majority of the dimming systems currently employed use Infrared (IR) motion sensors to detect vehicle motion on the streets [70]. However, the IR sensors suffer from their short range, the possibility of being affected by weather conditions and the fact that they do not measure the speed, which are important for speed and traffic monitoring. Given these disadvantages, few companies have started to provide RF motion sensors to detect vehicle and pedestrian motion on the streets.

5. Smart Lighting Connectivity

To have an outstanding smart lighting system, connectivity is required between the elements. A wireless smart lighting connectivity was introduced in 2012 as ZigBee Light Link (ZLL), which aimed to provide a global standard to ease the use of lighting. ZigBee in general has data transfer rates that can go up to 2500 kbps, which is enough to transmit and receive light commands. There are many other wireless connectivity options that were introduced later, such as Wi-Fi standard as well as Bluetooth standard and Bluetooth Low Energy (LE) 4.0 standard. Compared to ZigBee, Bluetooth and Wi-Fi have very high data transfer rates that can go up to 1 Mbps and 1300 Mbps, respectively [35]. One key difference between ZigBee and the other two options is that they do not require a bridge and the light bulb can be controlled directly from a user's cell phone. ZigBee and Bluetooth are low in cost and power consumption; however, Wi-Fi is more expensive and higher in power consumption.

Table 2: Comparison between Li-Fi and Wi-Fi.

Parameter	Li-Fi	Wi-Fi
Security	More secure	Less secure
Frequency	1000 times of THz	2.4-5 GHz
Transmitter	LED	Antenna
Receiver	LED	Antenna
Power consumption	Less	More
Efficiency	More	Less

Visible Light Communication (VLC) is another way to transmit information through LEDs. Li-Fi is based on VLC and it is known as light-based Wi-Fi as it transmits data through light instead of radio waves. The difference between Li-Fi and VLC is that VLC has unidirectional and point-to-point light communication; however, Li-Fi uses fully networked, bidirectional wireless communication. There are many advantages of Li-Fi over Wi-Fi; Li-Fi uses light for transmission instead of radio frequencies. Therefore, it has a large bandwidth. In terms of security, Wi-Fi uses radio frequency to transmit data and it may go through obstacles and may be exposed to security issues; however, Li-Fi is more secure as it uses light waves [35]. Table 2 shows more comparisons between Li-Fi and Wi-Fi.

Despite the numerous advantages of Li-Fi, it has some disadvantages such as interfering with other light sources and sensitivity to weather conditions.

Wireless communication between nodes for street lighting is also discussed in the literature [71, 72]. Nevertheless, street lighting has become part of Internet of Things (IoT) projects. All sensors in this network type are connected to exchange valuable data with each other, other devices, or systems over the internet [73–76]. Some researchers [76–78] have employed the Long Range (LoRa) for connectivity. LoRa uses free unlicensed ISM bands at a lower frequency; for example, it is 433 MHz for Asia, 868 MHz for Europe, and 915 MHz for North America [79]. LoRa technology supports communication up to 5 km in urban, 18 km in suburban, and 48 km in rural areas when compared with other traditional systems, namely, Bluetooth, WLAN, and ZigBee [77, 78]. Bluetooth has a very short range (10 m) while ZigBee and Wi-Fi systems also provide only up to 100 m range. LoRa technology offers a very low data rate, thus lowering the power consumption and increasing the battery's lifetime. It supports star topology which ensures scalability and fault tolerance to the network. Each device can independently communicate with the hub and provide a means of centralized management to monitor the network. It uses a chirp spread spectrum in the 868 MHz band [77]. A Smart Street Light Management System was developed using LoRa technology to automate the operation of the street light, meeting the requirements of vehicles and travelers [80]. It was found that deploying the smart street light system using LoRa helped in saving energy, detecting faulty street lamps, and in reducing manual surveillance on each pole. The performance of low-power wide-area networks was analyzed based on LoRa technology, namely, Doppler robustness, scalability, and coverage [81]. This study showed that with a transmit power of 14 dBm and a spreading factor of 12, more than 60% of packets could be received for a distance of 30 km.

Recent smart street light systems have employed Narrow Band IoT (NBIoT) for connectivity [82]. Such smart street lighting systems are combined with NBIoT network, IoT platform, and cloud computing of telecom operators to realize light monitoring and other functions. NBIoT utilizes LTE cellular infrastructure. This means the networks are outdoor public networks where there are 4G/LTE cellular towers. NBIoT has some advantages over LoRa in terms of larger coverage distance, more penetration distance, and being part of the licensed spectrum [82]. For customers searching for a more secure industrial IoT solution, it should be noted that NBIoT is built on 256-bit 3GPP encryption that is more secure than LoRaWAN and its AES 128-bit encryption. NBIoT can exist together with 2G, 3G, and 4G mobile systems, therefore benefiting from the security and privacy features of these systems [83–92].

The study in [40] focused on improving the level of power saving through different lookup table schemes for light dimming. The paper showed that the instantaneous dimming of the light intensity level prevented the spike in load power and was inversely proportional to the distance of the moving vehicle. A decentralized LED light dimming system with unlimited dimming levels was proposed in [93]. The study showed that additional energy saving could be achieved through the analog control of light dimming based on the instantaneous output voltage of an RF sensor. The merits of the decentralization technique were achieved by fixing the dimming circuit on each pole lamp. A diagnostic system for monitoring street light lamps was proposed and implemented [93]. It continuously measured the lamp's load current as an indicator of the lamp's health. The lamp status was displayed on a liquid crystal display. The system was, as well able through GSM connectivity to send an SMS message to the system operator's mobile phone with a notification about the status of the lamp. The proposed system idea, which is described in Figure 1, forms one of the most important functionalities a smart street lighting system can build on.

A design verified through simulation results was proposed in [95] for a decentralized smart street LED light-dimming system. This proposed system offered two advantages, energy saving through the use of LED lamps and automatic, real-time light-dimming capability that ensured that the dimming was a function of the car's speed measured by the motion sensor. Figure 2 shows the decentralized local dimming system proposed by [95], which was characterized

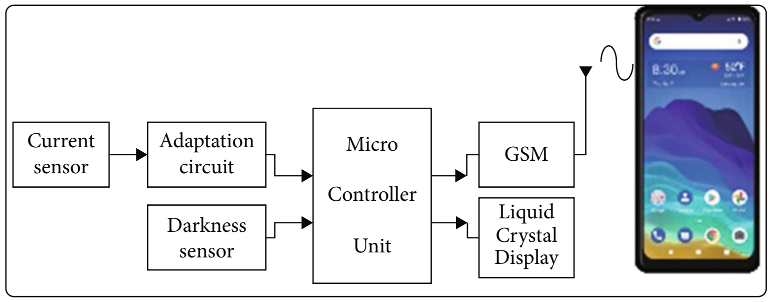

FIGURE 1: Block diagram of the proposed wirelessly diagnostic system of [94].

by simplicity and fast response. A smart street lighting system, which can control the light intensity of each lamp based on the traffic and weather conditions, was designed with the help of an IoT network [96].

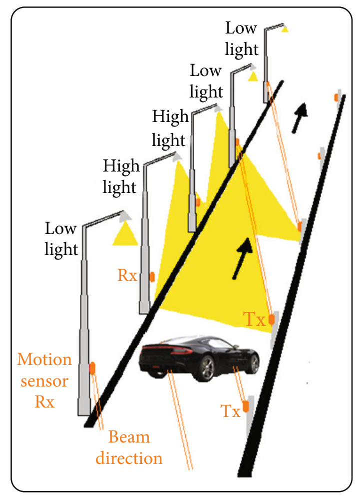

FIGURE 2: Street light dimming using a decentralized process [96].

6. Summary of Performance Parameters of Smart Street Lighting Research

Table 3 shows a summary of the performance parameters of some of the research work investigated in this paper. In summary, decentralized systems in which the dimming action is done on the light pole have a faster response as compared to centralized systems where the change of light intensity is done at a centralized server via a communication link. The centralized systems where the poles are connected through a communication network enjoy automatic light failure detection and weather conditions monitoring. A hybrid system with a decentralized dimming function and centralized diagnostics and weather monitoring enjoys the speed of response as well as diagnostics and weather-monitoring capabilities. Table 3 provides a general review that shows the different technologies implemented for smart street light systems.

Table 3 compares between the different papers in terms of the level of energy saving, the lighting system used whether it is centralized, decentralized, or hybrid as explained in Section 5, light dimming response speed, type of lamp used whether it is LED or other type, the lamp failure detection system whether it is manual or automatic, the ability to monitor and record weather conditions, the immunity of the system to intrusion and hacking, the wireless technology used whether it is 4G, ZigBee, IoT, GPRS, etc., the type of sensor used whether it is PIR, RF, ultrasonic, etc., and if the system light is dimmable or not.

7. Current and Future Trends in Lighting Systems

As explained in Section 5, there are three types of smart lighting systems currently being implemented. The first is a centralized control system where the signal coming out of the motion sensor is sent wirelessly to a remote-control station which will send the control signal back to the light poles for light dimming action. The second system is a decentralized system where the light intensity control is done locally at each pole. The third system is a hybrid system where the light intensity control is localized on each light pole while the connectivity is used to convey weather information and for lamp failure diagnostics.

Including cybersecurity in the design of future smart lighting systems will be an important trend in the near future, as cybersecurity will be a major concern for smart street lighting systems [4, 97, 98]. This will make the proposed smart system immune to interference and cyberattacks. The use of artificial intelligence techniques to help predict the traffic movement and reduce the load on smart street lighting systems is expected to be an important future trend [99, 100]. The use of light poles to provide charging for electric vehicles will also be an important trend. In-house RF motion and speed sensor instead of PIR motion sensor built using the reliable and power-saving CMOS technology with antenna integrated on the same package for cost reduction and performance improvement is an important area of research. Cheaper traffic speed monitoring using in-house RF speed sensors and LPR cameras installed on light poles will attract more research [101–104]. Selection of the suitable type of LED lamps that can work efficiently even in bad weather conditions to provide comfort to the driver will become more important for smart street lighting. Continuous sensor-controlled automatic dimming instead of scheduled 2-level dimming is expected to give more energy saving [93]. Design and installation of LPWAN IoT communication network

Table 3: Summary of the performance parameters of several sited research in this paper.

Paper reference	Energy saving	Topology (centralized or decentralized)	System speed	Lamps used LED or not	Automatic lamp failure detection	Weather monitoring	System security immunity to intrusion (hacking)	Wireless technology used	Sensor type	Dimming
[32]	High	Centralized	Slow	LED	No	No	Yes	IoT	PIR	Yes
[57]	High	Decentralized	Fast	LED	No	No	No	IoT	IR	Yes
[58]	High	Centralized	Slow	LED	Yes	Yes	No	GSM	PIR	Yes
[59]	High	Centralized	Slow	LED	No	Yes	No	GPS/ GPRS/4G	PIR	Yes
[60]	High	Centralized	Slow	LED	No	No	No	WSN	PIR	Yes
[62]	High	Centralized	Slow	LED	Yes	No	No	GPRS	—	Yes
[62]	High	Centralized	Slow	LED	No	No	No	ZigBee	PIR	Yes
[67]	High	Centralized	Slow	LED	Yes	No	Yes	GSM	NIC photocell	Yes
[68]	High	N/A	N/A	LED	No	No	No	N/A	Chip	Yes
[69]	High	Centralized	Slow	LED	Yes	No	No	IoT	Ultrasonic	Yes
[70]	High	N/A	N/A	LED	No	No	No	Not yet	PIR	Yes
[72]	High	Centralized	Low	LED	No	No	No	GSM	PIR	Yes
[73]	High	Centralized	Low	LED	No	No	No	GPS/ GPRS/ GSM/IoT	—	Yes
[75]	High	Centralized	Low	LED	No	No	No	ZigBee	Motion sensor	Yes
[76]	High	Centralized	Low	LED	No	No	Yes	ZigBee	—	ON-OFF
[79]	High	Centralized	Low	General	Yes	No	No	LoRa	N/A	ON-OFF
[82]	N/A	Centralized	Low	LED	N/A	N/A	N/A	NBIoT	N/A	N/A
[95, 96]	High	Hybrid	High	LED	Yes	Yes	Yes	NBIoT	RF motion and speed sensor	Continuous

that employs one of the following protocols, NB-Fi of NB-IoT, that offer power and cost saving and compatibility with IoT for smart cities are important for future smart cities [82, 95, 96]. Feasibility and cost analysis of the potential use of light poles as communication towers or Wi-Fi terminals are a potential area of concern. Fuzzy logic controller to provide a priority signal from the coordinator pole to the other poles to override the motion sensor signal in emergency conditions and ability to detect and report accidents or traffic congestions are also important. Above all, we believe it is the integration of all these features in one smart street lighting system will be a main target for future smart street lighting.

8. Conclusions

In this paper, many studies in the field of smart street lighting systems are reviewed, and the details of the systems' merits and demerits in terms of response speed and energy-saving effectiveness are demonstrated and compared. The paper explained the three types of smart systems that are available now including the centralized, noncentralized, and hybrid systems. The authors suggest that the hybrid system is more useful as it enjoys the benefits of the other two systems in terms of speed of response and ability to do remote lamp diagnostics and convey weather information. A full comparison between the different systems is also provided. Several current and future trends are highlighted.

Data Availability

There is no data displayed in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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